Bulletin of the *Transilvania* University of Braşov
Series I: Engineering Sciences • Vol. 5 (54) No. 2 - 2012

PHASE ANGLE CONTROL IN A SERIES RLC CIRCUIT USING AN ELECTRONICALLY SWITCHED CAPACITOR

R. MERA[1]   R. CÂMPEANU[1]

Abstract: *In this article the principle of the switched capacitor in a series RLC circuit is presented. The classical methods for phase angle control are described, and a novel control method, where the capacitor is placed in the centre of a bidirectional H bridge switches. Using an electronic circuit simulation program, the representative voltage and current curves are obtained. The phase angle at various transistor switching frequencies is determined. Also a study of the capacitor value and the switching frequency on the duty ratio resolution and phase angle is performed. The experimental results confirm the data acquired from computer analysis.*

Key words: *switched capacitor, phase angle control.*

1. Introduction

A well-established capacitor value from a series RLC circuit determines a precise phase angle between source's voltage and current. Thus continuously modifying the capacitor the phase angle can be kept at optimal value and the circuit performance enhanced.

The principle can be implemented on a capacitor-run single phase induction motor which has a capacitor in series with the auxiliary winding. It is well known that a high capacitor determines a high starting torque, but a low running efficiency. The run-capacitor is a few times smaller than the start-capacitor.

Hence this principle can be successfully used for single phase induction electrical drives.

The gyrator concept is used to generate high capacitor values. The main problem is the concept implementation on power electronics. In [1] was proven the some power converters can be used as gyrators.

The electronic control was an alternative and was used for inductive effects control.

2. Electronically Controlled Capacitor Methods

Two classic methods for capacitance electronic control using power switches are available. Liu [3] and Muljadi [5] place in parallel with the capacitor a bidirectional switch (two back to back transistors). It is periodically closed and opened. The principle is presented in Figure 1.

If the switch is open, the current will flow thought the capacitor, hence the circuit is series RLC. The current will flow thought the switch when it is closed. It will

[1] Dept. of Automatics, *Transilvania* University of Braşov.

be reopened only when the capacitor voltage reaches zero, so a zero voltage switching (ZVS) is performed.

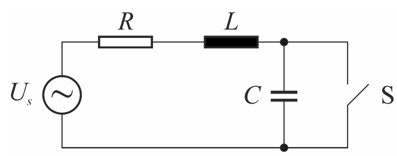

Fig. 1. *Liu and Muljadi Switched Capacitor Principle* (*SCP*)

The emulated capacitor value can be varied if the fundamental component of the voltage on the switch varies independent of the current flowing through it.

Periodically closing and opening the switch the fundamental component of the voltage appears lower than a classic RLC circuit. Thus the capacitor value tends to increase.

In this circuit are 2 different cases: first a RL circuit described by:

$$\frac{\mathrm{d}i}{\mathrm{d}t}=\frac{u-Ri}{L},\qquad \frac{\mathrm{d}u_c}{\mathrm{d}t}=0, \tag{1}$$

and in the second case, a series RLC circuit with the following equations:

$$\frac{\mathrm{d}i}{\mathrm{d}t}=\frac{u-Ri-u_c}{L},\qquad \frac{\mathrm{d}u_c}{\mathrm{d}t}=\frac{i}{C}. \tag{2}$$

Using a computer calculus programs the waveforms from Figures 2 and 3 are obtained: supply voltage-blue, supply current-red and capacitor voltage-black. The circuit's current is quite distorted. Also, the capacitor voltage is influenced by the control angle (γ).

For a control angle close to 10 ms the current is severe distorted and the capacitor voltage amplitude increases.

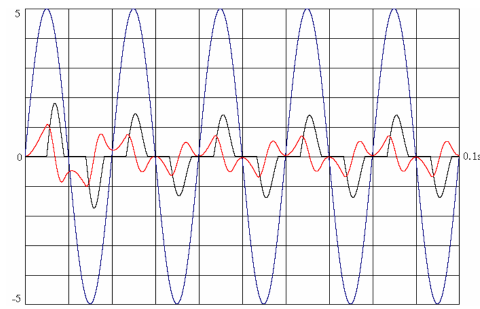

Fig. 2. *Current and capacitor voltage for γ = 0.005 s*

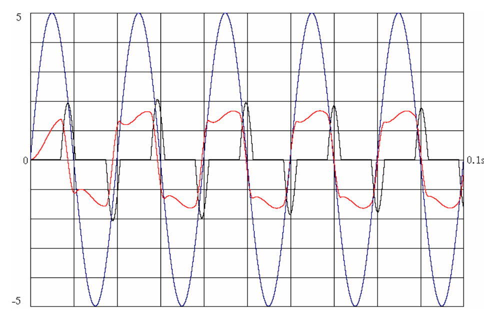

Fig. 3. *Supply current and capacitor voltage for γ = 0.007 s*

Lettenmaier [2] uses a dc capacitor (electrolytic type) placed in the middle of an H bridge. The bridge is pulse width modulated, and the capacitor is charged from the supply voltage. The capacitance is high enough to eliminate the voltage ripple. The bridge output voltage is pulse width modulated and the phase angle between the supply voltage and the bridge voltage controls the transistor switching frequency. In Figure 4 the principle is presented.

The methods previously described are used for capacitor-start/capacitor-run energy efficiency improvement.

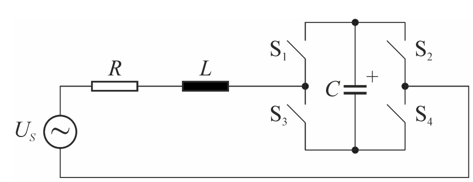

Fig. 4. *Lettenmaier's SCP method*

3. Novel Switched Capacitor Principle

In [6] a novel type of switched capacitor is presented. It will be used in the phase angle and amplitude control of the auxiliary winding current of the capacitor-run single phase induction motor.

An AC capacitor is placed in the middle of a bidirectional 4 switches H bridge. The power circuit and the control circuit are next detailed.

3.1. The power circuit

In Figure 5 the power circuit is presented. Every group (A, B, C or D) represents a bidirectional switch. The Power MOSFET transistors (IRFBC40) and ultrafast switching diodes (RURP860) were used for the switch. The ON resistance of the field effect transistor is about 1.2 Ω.

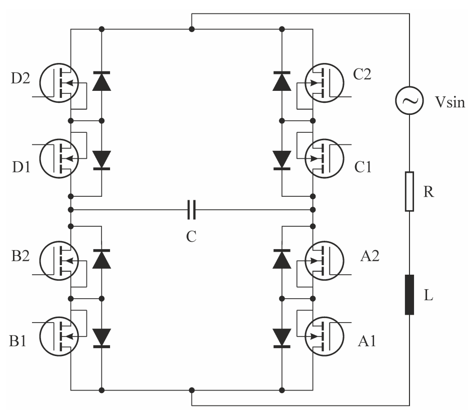

Fig. 5. *Novel SCP*

The freewheel diodes support the same reverse voltage and direct current as the transistor, and have a reverse recovery time of a few nanoseconds. The common source connection simplifies the control circuit and ensures a current flow control for the full-wave.

Each transistor is protected for transitory voltages by a RC group placed in parallel with the diode and transistor.

3.2. The control system

In is important that the pairs of switches A, D and B, C do not permit simultaneously current flow. If they do the capacitor is short circuited. The capacitor discharge path should be through the RL circuit. The following groups form the control circuit:

- Pulse generator;
- Delay circuit;
- Transistor gate drivers with separate DC power supply.

The first two were afterwards replaced with an electronic board *Arduino Uno*. The solution was adopted due to the simplicity of programming and the high resolution provided by the Atmel microcontroller. The board allows a precise control of the duty factor, of the frequency and of the delay time between the two control signals. A transistor current amplifier was constructed due to the board's low current outputs.

In Figure 6 the control system is presented. There are 4 identical circuits for each switching cell. Each power MOSFET

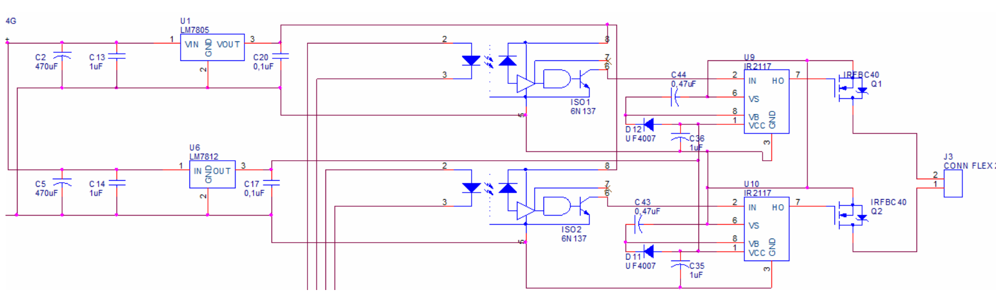

Fig. 6. *Switched capacitor driver system*

is controlled by an IC IR2117. The control signal is received from the board through a 6N137 opto-isolator. The transformer and the rectifier are intentionally ignored from Figure 6.

The transformer, including the optocoupler, galvanic separates the transistors control signals from the power supply and between different control circuits.

4. Computer Simulation Results

The series RLC circuit used for the simulation has the following parameters: R = 10 Ω, L = 60 mH, C = 10 μF. Without a capacitor the phase angle is of 32.4 degrees. A low voltage power supply was used to determine the voltage surges generated by the forced inductive switching. The study has the objective of using the electronically controlled capacitor for the efficiency improvement of single phase induction motors.

The computer simulations were performed using a dedicated circuit simulation program, PSPICE using the libraries of the IRFBC40 transistors. The control circuit presented in Figure 6 was simplified and replaced with a pulse generator and a gate resistance. The generated data were imported into Matlab for analysis and graphical representation.

The equation for emulated capacitance is:

$$C_e = \frac{C}{(2d-1)^2}, \quad (3)$$

where d is the duty ratio. Thus for a duty ratio of 0.5 the capacitance is theoretically infinite.

In Figure 7 are presented the supply voltage and supply current waveforms for a duty ratio of 0.5. The waveforms lack the harmonic content. A coefficient of 1/50 was applied to the voltage for easier visualisation. The current is shifted forwards by 51.17 degrees.

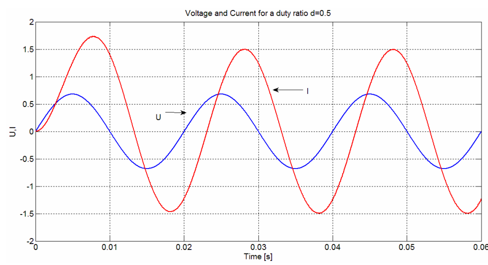

Fig. 7. *Voltage and current for d = 0.5*

In Figure 8 are presented the same waveforms for a duty ratio equal to 0.8. The supply voltage and current are in phase but the harmonic content increases. The supply current amplitude also decreases.

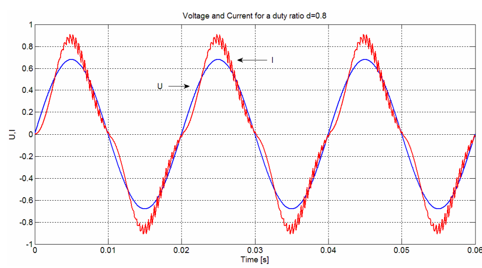

Fig. 8. *Voltage and current for d = 0.8*

In Figure 9 are depicted the supply and capacitor voltages. Both are multiplied by 0.5 and a duty ratio of 0.5. The complete discharge of the capacitor can be observed.

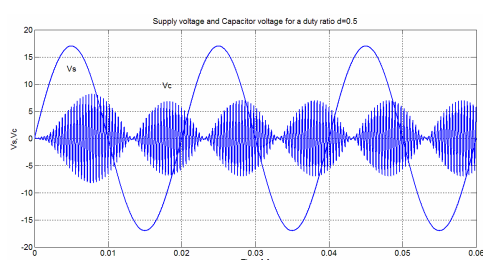

Fig. 9. *Supply and Capacitor voltage for d = 0.5*

In Figure 10 are presented the same voltages for a duty ratio of 0.8. The capacitor voltage has a maximum value double than the supply voltage. Due to the high ratio of charging and discharging time the capacitor doesn't discharge completely.

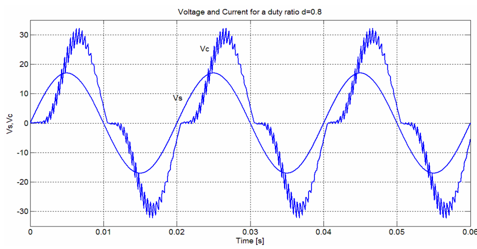

Fig. 10. *Supply and Capacitor voltage for d = 0.8*

The capacitor voltage waveform has a similar shape of the current in Figure 8.

In Figure 11 are depicted the transistor voltages, the supply voltage and freewheel diode current. The surge voltages that appear on the power MOSFET are divided by 2. For the negative wave, the low transistor voltage appears due to the current in the parallel diode and the generated voltage drop. The voltage lags the current due to the capacitor placed in parallel with the transistor. The study of the effects on voltages of the transistor protection RC group will continue.

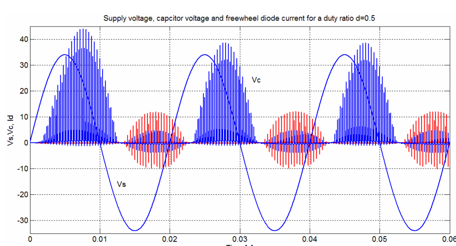

Fig. 11. *Supply voltage, Capacitor voltage and freewheel diode current for d = 0.5*

In Figure 12 in presented a detailed description of the forward transistor voltage drop and the switching transients are visible. In this case the diode current in null.

The graphs were generated for a switching frequency of 2.5 kHz, and a delay time of 1 µs. The turn off time of the power MOSFET parasitic diode is around 920 ns.

The simulations were performed at different frequencies (0.75 kHz to 3.4 kHz) to establish the largest variation of the phase angle. The 2.5 kHz proved to be the most important.

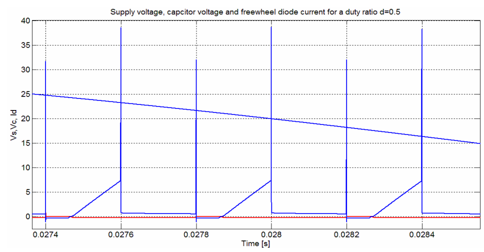

Fig. 12. *Detailed description of the transistor forward voltage drop*

Different simulations were performed for various RC protection groups. Notable differences were observed. The switching and on losses will be further analysed.

In [4] were determined the optimal capacitor values for a single phase induction motor. The maximum capacitor value at which the thermal protection does not disconnect the motor is around 20 µF. Simulations were performed for different capacitor values and various duty ratios. The most important conclusions are:

- The duty ratio decreases as the capacitor increases;
- The capacitor surge voltages decrease as the value increases;
- The switching frequency affects the current's amplitude.

5. Experimental Results

Using the same RLC circuit parameters and supply voltage amplitude experimental testing was performed.

With a digital oscilloscope the voltage and current waveforms were saved. A galvanic insulation of the oscilloscope's supply voltage was necessary.

The transistors used in the experiments are identical with the ones used in the simulations. Freewheel diodes are missing from the experimental setup, instead are used the internal parasitic diodes.

In Figure 13 are presented the voltage and current for a duty ratio of 0.5 (left) and 0.8 (right).

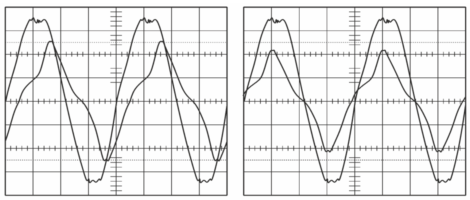

Fig. 13. *Experimental acquired supply voltage and current*

For the supply voltage channel is 10 V/div, respectively 1 V/div for the supply current. The time base is 5 ms/div.

The simulation results are confirmed by experimental testing.

6. Conclusions

The implemented system using bidirectional switches and MOSFET power transistors controls very accurate the phase angle between supply's voltage and current. It was fully implemented and the experimental results confirmed the simulations.

The concept can be used in the efficiency improvement of a capacitor-run single phase induction motor.

Acknowledgment

This paper is supported by the Sectorial Operational Programme Human Resources Development (SOP HRD), ID59321 financed from the European Social Fund and the Romanian Government.

References

1. Divan, D.M.: *Nondisipative Switched Networks for High-Power Applications*. In: Electronics Letters **20** (1984) No. 7, p. 277-279.
2. Lettenmaier, T.A., et al.: *Single-Phase Induction Motor with an Electronically Controlled Capacitor*. In: IEEE Transactions on Industry Applications **27** (1991) No. 1, p. 38-43.
3. Liu, T.H.: *A Maximum Torque Control with a Controlled Capacitor for a Single-Phase Induction Motor*. In: IEEE Transactions on Industrial Electronics **42** (1995) No. 1, p. 17-24.
4. Mera, R., Câmpeanu, R.: *Optimal Performance of Capacitor-Run Single Phase Induction Motor*. In: Proceedings of the 13th International Conference on Optimization of Electrical and Electronic Equipment, Braşov, Romania, May 24-26, 2012, p. 718-723.
5. Muljadi, E., et al.: *Adjustable AC Capacitor for a Single-Phase Induction Motor*. In: IEEE Transactions on Industry Applications **29** (1993) No. 3, p. 479-484.
6. Suciu, C., et al.: *Phase Advancing for Current in R-L Circuits Using Switched Capacitors*. In: Electronics Letters, IEE Journal **35** (1996) No. 16, p. 1296-1927.